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Technology Choice and Incentives under Relative Performance Schemes*

Matthias Kräkel† Anja Schöttner‡

Abstract

We identify a new problem that may arise when heterogeneous workers are motivated by relative performance schemes: If workers' abilities and the production technology are complements, the firm may prefer not to adopt a more advanced technology even though this technology would costlessly increase each worker's productivity. Due to the complementarity between ability and technology, under technology adoption the productivity of a more able worker increases more strongly than the productivity of a less able colleague, thereby reducing the motivation of both workers to exert effort under a relative incentive scheme. We show that this adverse incentive effect is dominant and, consequently, keeps the firm from introducing a better production technology if talent uncertainty is sufficiently high and/or monitoring of workers is sufficiently precise.

Key Words: complementarities; heterogeneous workers; production technology; tournament.

JEL Classification: D82; D86; J33; M52.

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1 Introduction

A fundamental incentive problem in organizations arises from the fact that workers' individual performance signals are often unverifiable, i.e., they are observable by the firm but not by a third party. In such a situation, popular incentive schemes like bonuses and piece rates cannot be used because of potential employer opportunism: Ex-post the firm can save labor costs by wrongly claiming that workers have performed poorly. Since workers anticipate such opportunistic behavior, incentives would be completely erased.

However, when performance measures are unverifiable, the firm can still rely on relative incentive schemes or rank-order tournaments for incentive provision (Malcomson 1984, 1986).[1] In practice, we can observe diverse variants of relative incentive schemes, e.g., job-promotion tournaments (Baker, Gibbs and Holmström 1994, Treble, van Gameren, Bridges and Barmby 2001), sales contests (Kalra and Shi 2001; Murphy, Dacin and Ford 2004; Lim, Ahearne and Ham 2009), forced-distribution systems (Murphy 1992; Thomas 2002), and bonus pools (Kanemoto and MacLeod 1992; Rajan and Reichelstein 2006, 2009; Budde 2009). Under each variant, the firm commits to pay a certain collective amount of money to the workers. Such a commitment is credible because a third party can verify whether the collective amount has been paid out by the firm. This collective money is distributed among the workers according to their relative performance. Since the firm is forced to pay out the total amount of money, it has no incentive to misrepresent the workers' performance. This important self-commitment property assures worker incentives.

In this paper, we point out that the use of relative performance schemes can be highly problematic if the firm can choose between different production technologies. We characterize situations in which the firm foregoes to install a new technology although this technology would increase each worker's pro-

[1] Another well-known solution to the unverifiability problem are relational (or self-enforcing) contracts (see, e.g., Bull 1987; Baker, Gibbons and Murphy 2002). For a relational contract to be feasible, the firm's loss from reneging must be sufficiently large, e.g., the employer-employee relationship needs to be sustained with sufficiently high probability in the future and the associated future profit must not be discounted heavily.

ductivity and is costlessly available. When choosing the technology, the firm faces the following trade-off: On the one hand, a more advanced technology enhances each worker's productivity (*productivity effect*). On the other hand, if worker ability and firm technology are complements and workers differ in their abilities, the new technology increases the productivity of a more able worker more strongly than the productivity of a less able worker. Thus, the outcome of the tournament is less responsive to changes in effort and, consequently, both workers exert less effort (*adverse incentive effect*). If the adverse incentive effect dominates the productivity effect, the firm will not adopt the advanced technology.

In a next step, we use a parameterized example to highlight the impact of worker heterogeneity on technology choice. We show that, the higher the degree of worker heterogeneity and the higher the uncertainty about workers' ex-ante unknown talents, the more likely the firm will choose the less productive technology. In particular, we compare two labor market situations that differ in the expected ability of the worker pool. We demonstrate that the firm may adopt the more advanced technology only in the situation where the worker pool is of lower average quality. Such a situation occurs if talent uncertainty in the worker pool of higher average ability is sufficiently high compared to the pool of lower average quality. Furthermore, if workers' equilibrium efforts are rather small under either technology due to imprecise performance measurement or steep marginal effort costs, the adverse incentive effect of technology adoption is not severe. As a result, if the firm's monitoring technology is imprecise, the firm is more inclined to invest in a better production technology. Hence, if worker ability and production technology are complements in the firm's production function, monitoring technology and production technology are substitutes.

The theoretical setting with ability and technology being complements fits well with the situation observed in the last decades where firms intensely invested in information technologies (IT). Initially, investment in IT was used to save labor and to substitute capital for low-ability work. However, nowadays IT and workers' abilities are mainly seen as complements (see, among many others, Applegate, Cash and Mills 1988; Berndt, Morrison and Rosenblum 1992; Hitt and Snir 1999; Bresnahan, Brynjolfsson and Hitt 2002). IT is used by high-ability workers for improving time to market in research and development and improving service to key customers, for example. In other words, rather complex IT is used by firms for intensively exploiting the potential of their high-ability workers, hence making them more productive.

Besides the literature cited above, our paper is related to the work on rank-order tournaments starting with the seminal articles by Lazear and Rosen (1981) and Nalebuff and Stiglitz (1983). Subsequent papers pointed to specific disadvantages of tournaments. Two major problems of tournaments have been emphasized in the literature. First, workers can improve their relative positions in the ranking by investing in counterproductive effort or sabotage (Lazear 1989; Konrad 2000; Chen 2003; Münster 2007; Amegashie and Runkel 2007; Gürtler 2008). Second, similar to cartels in market competition, tournament participants can collectively gain by a stable collusion that minimizes effort costs (Ishiguro 2004; Amegashie 2006; Chen 2006; Sutter and Strassmair 2009). In this paper, we identify a further problem of tournaments – an adverse effect on technology choice given that worker ability and production technology are complements.

The remainder of the paper is organized as follows. In the next section, we introduce the model setup. Section 3 solves the workers' problem of effort choice in the tournament. Section 4 focusses on the firm's problems of designing optimal tournament prizes and choosing the optimal production technology. O'Keeffe, Viscusi, and Zeckhauser (1984) and Schotter and Weigelt (1992) differentiate between two ways of modeling tournaments with heterogeneous contestants – so-called "unfair" and "uneven" contests. Until Section 4, the paper considers the case of unfair tournaments, in which heterogeneous workers choose the same effort levels in equilibrium. To check robustness of our findings, Section 5 turns to the case of uneven contests with asymmetric equilibria. We show that the crucial economic effects are still present in this more complicated case. Section 6 concludes.

2 The Model

We consider a firm that employs two workers. All parties are risk neutral. Workers are protected by limited liability so that all payments to them must be non-negative. Worker i ($i = 1, 2$) produces the monetary output $h(e_i, a_i, \tau) + \varepsilon_i$. Here, $e_i \geq 0$ denotes worker i's effort choice, a_i is the worker's exogenously given ability, and τ characterizes the firm's production technology. Furthermore, ε_i is a random variable, where ε_1 and ε_2 are identically and independently distributed. Let $G(\cdot)$ denote the cdf of $\varepsilon_2 - \varepsilon_1$ and $g(\cdot) = G'(\cdot)$ the corresponding density. We assume that $g(\cdot)$ is single-peaked at zero.[2]

The technology parameter $\tau \in \{\tau_L, \tau_H\}$ is chosen by the firm. It can either use a more advanced technology $\tau = \tau_H$ or a less advanced one $\tau = \tau_L < \tau_H$. For simplicity, we assume that technology adoption is free.[3] Output is strictly increasing in effort, ability, and the technology parameter, i.e., $\frac{\partial h}{\partial e_i}, \frac{\partial h}{\partial a_i}, \frac{\partial h}{\partial \tau} > 0$. In particular, this means that, holding effort constant, a better technology increases the output of each worker. Furthermore, output is concave in effort, i.e., $\frac{\partial^2 h}{\partial e_i^2} \leq 0$. The marginal productivity of effort increases with a better technology, i.e., $\frac{\partial^2 h}{\partial e_i \partial \tau} \geq 0$. However, we do not impose a restriction on the sign of $\frac{\partial^2 h}{\partial a_i \partial \tau}$, implying that technology and ability can be substitutes or complements. In case of substitutes ($\frac{\partial^2 h}{\partial a_i \partial \tau} \leq 0$), the marginal productivity of ability decreases under the better technology. Put differently, productivity differences due to distinct abilities are evened out because the advanced technology increases the productivity of less able workers more strongly. For example, this happens if the new technology makes the production task easier for workers of lower ability, so that they can keep up with more capable colleagues. Such a situation might occur if the firm adopts an easier-to-handle computer operation system, like switching from MS-DOS

[2] The assumption of a unimodal distribution is common in tournament models; see, e.g., Dixit (1987), Drago et al. (1996), Hvide (2002), or Chen (2003). It holds for many distribution functions. For example, if ε_1 and ε_2 are normally distributed, the convolution $g(\cdot)$ is again normal. If ε_1 and ε_2 are uniformly distributed, the distribution of $\varepsilon_2 - \varepsilon_1$ will be triangular.

[3] In practice, technology adoption is typically costly, where the adoption of a more advanced production technology is more expensive to the firm. Thus, introducing costs for technology adoption would only reinforce our result that the firm may prefer the less productive technology.

to MS-Windows. By contrast, if technology and ability are complements ($\frac{\partial^2 h}{\partial a_i \partial \tau} > 0$), more able types benefit more from the advanced technology, e.g., if the new technology is complex and difficult to handle (as replacing typewriters with personal computers). Finally, to simplify the analysis, we assume that the marginal productivity of effort does not interact with ability, i.e., $\frac{\partial^2 h}{\partial e_i \partial a_i} = 0$.[4]

A worker's ability can be either high or low, $a_i \in \{a_L, a_H\}$, where $a_H > a_L \geq 0$. The probability that a worker is of high ability is denoted by $p \in (0,1)$ and is common knowledge. After accepting the contract offered by the firm and entering into the employment relationship, each worker becomes familiar with the task to be conducted in this particular firm, and can thus assess how good he will be at it. Consequently, every worker learns his own ability. Moreover, each worker also observes the type of his colleague, whereas the firm never observes workers' abilities. This assumption captures the fact that employees who work closely together usually possess better information about one another's talents than the firm. For simplicity, an agent's reservation utility is zero.

Worker i's costs of effort are $c(e_i)$ with $c'(e_i), c''(e_i) > 0$ for all $e_i > 0$, and $c(0) = 0$. To guarantee interior solutions, we further impose the restriction that $\frac{\partial h}{\partial e_i}(0, a_i, \tau) > c'(0)$, and to ensure concavity of the firm's objective function, we impose $c'''(e_i) > 0$ for all $e_i > 0$. A worker's effort choice is unobservable, whereas his output is observable by the parties within the firm but unverifiable to outsiders. Thus, individual pay-for-performance schemes are infeasible. Therefore, the firm employs a rank-order tournament to provide its workers with effort incentives.[5] In a rank-order tournament,

[4] The assumption $\frac{\partial^2 h}{\partial e_i \partial a_i} = 0$ implies that we focus on the analysis of "unfair contests" in the sense of O'Keeffe, Viscusi, and Zeckhauser (1984) and Schotter and Weigelt (1992), who differentiate between "unfair" and "uneven" contests as two alternative ways of modeling heterogeneous players. In unfair contests, players exerting the same effort level have different winning probabilities. Technically, effort and ability additively enter the production function, leading to symmetric equilibria. However, in uneven contests effort and ability are multiplicatively connected (either in the production or the cost function), thus yielding asymmetric equilibria. We briefly discuss uneven contests in Section 5.

[5] See Malcomson (1984, 1986) on the self-commitment property of tournaments that allows their application in situations with unverifiable performance signals.

the worker with the higher output obtains the winner prize w, whereas the other worker receives the loser prize l, $w > l$. Due to workers' limited liability, both prizes must be non-negative.

Timing is as follows. At the first stage, the firm makes the technological choice $\tau \in \{\tau_L, \tau_H\}$, which is publicly observable. Thereafter, it offers two randomly chosen workers a contract specifying tournament prizes w and l. Given that workers accept, they enter the firm and observe abilities. In stage 3, workers simultaneously choose their effort levels. Then, the random variables ε_1 and ε_2 are realized and each worker's output is observed. Finally, the tournament prizes are paid.

3 Workers' Effort Choices

In this section, we derive workers' equilibrium effort levels given the firm's technological choice and the tournament prizes w and l. When workers choose effort, they know the technology parameter τ. Thus, given the effort choice e_2 of worker 2, worker 1 chooses effort e_1 to solve

$$\max_{e_1} l + G(h(e_1, a_1, \tau) - h(e_2, a_2, \tau)) \cdot (w - l) - c(e_1).$$

Similarly, worker 2 chooses e_2 to solve

$$\max_{e_2} l + [1 - G(h(e_1, a_1, \tau) - h(e_2, a_2, \tau))] \cdot (w - l) - c(e_2).$$

We assume that the functional forms are such that worker i's objective function is concave in e_i for all e_j $(i, j = 1, 2; i \neq j)$.[6] Thus, the equilibrium effort levels (e_1^*, e_2^*) are characterized by the two first-order conditions

$$g(h(e_1^*, a_1, \tau) - h(e_2^*, a_2, \tau)) \cdot \frac{\partial h}{\partial e_1}(e_1^*, \tau) \cdot (w - l) - c'(e_1^*) = 0, \qquad (1)$$

$$g(h(e_1^*, a_1, \tau) - h(e_2^*, a_2, \tau)) \cdot \frac{\partial h}{\partial e_2}(e_2^*, \tau) \cdot (w - l) - c'(e_2^*) = 0. \qquad (2)$$

[6] This is the case if $[g'(h(e_i, a_i, \tau) - h(e_j, a_j, \tau)) \cdot (\frac{\partial h}{\partial e_i}(e_i, \tau))^2 + g(h(e_i, a_i, \tau) - h(e_j, a_j, \tau)) \cdot \frac{\partial^2 h}{\partial e_i^2}(e_i, \tau)] \cdot (w - l) - c''(e_i) < 0$ for all e_i, e_j, a_i, a_j.

Note that $\frac{\partial h}{\partial e_i}$ is independent of a_i because of our assumption $\frac{\partial^2 h}{\partial e_i \partial a_i} = 0$. Since $c'(e_i)/\frac{\partial h}{\partial e_i}$ is strictly increasing in e_i, the equilibrium is unique and symmetric, $e_1^* = e_2^* =: e^*$. Hence, defining $\Delta w := w - l$, equilibrium effort $e^*(a_1, a_2, \Delta w, \tau)$ is implicitly given by

$$g(h(e^*, a_1, \tau) - h(e^*, a_2, \tau)) \cdot \frac{\partial h}{\partial e_1}(e^*, \tau) \cdot \Delta w - c'(e^*) = 0. \tag{3}$$

Implicit differentiation of equation (3) leads to our first proposition.

Proposition 1 *If $\frac{\partial^2 h}{\partial a_i \partial \tau} > 0$ and $a_1 \neq a_2$, then $e^*(a_1, a_2, \Delta w, \tau)$ can be decreasing in the technology parameter τ. In particular, we obtain $\frac{de^*}{d\tau} < 0$ if $\frac{\partial^2 h}{\partial e_i \partial \tau} = 0$.*

Proof. Let $a_1 \neq a_2$.[7] By applying the implicit function theorem to equation (3), we obtain

$$\begin{aligned} sign\left(\frac{de^*}{d\tau}\right) &= \\ sign\Bigg(g'(h(e^*, a_1, \tau) - h(e^*, a_2, \tau)) &\left[\frac{\partial h}{\partial \tau}(e^*, a_1, \tau) - \frac{\partial h}{\partial \tau}(e^*, a_2, \tau)\right] \frac{\partial h}{\partial e_1}(e^*, \tau) \\ &+ g\left(h(e^*, a_1, \tau) - h(e^*, a_2, \tau)\right) \frac{\partial^2 h}{\partial e_1 \partial \tau}(e^*, \tau)\Bigg). \end{aligned} \tag{4}$$

Because $\frac{\partial^2 h}{\partial e_1 \partial \tau}(e^*, \tau) \geq 0$, the second term on the right-hand side of (4) is non-negative. Thus, we can obtain $\frac{de^*}{d\tau} < 0$ only if the first term on the right-hand side is negative. For $a_1 \neq a_2$ and $\frac{\partial^2 h}{\partial a_i \partial \tau} > 0$, we either have $g'(h(e^*, a_1, \tau) - h(e^*, a_2, \tau)) < 0$ and $\frac{\partial h}{\partial \tau}(e^*, a_1, \tau) - \frac{\partial h}{\partial \tau}(e^*, a_2, \tau) > 0$ (if $a_1 > a_2$) or $g'(h(e^*, a_1, \tau) - h(e^*, a_2, \tau)) > 0$ and $\frac{\partial h}{\partial \tau}(e^*, a_1, \tau) - \frac{\partial h}{\partial \tau}(e^*, a_2, \tau) < 0$ (if $a_1 < a_2$) because $\frac{\partial h}{\partial a_i} > 0$ and $g(\cdot)$ is single-peaked at zero. ■

Proposition 1 shows that, if ability and technology are complements and workers are heterogeneous, adopting an enhanced production technology may have an adverse effect on effort, i.e., decrease workers' equilibrium effort

[7] For $a_1 = a_2$, equation (3) boils down to $g(0) \cdot \frac{\partial h}{\partial e_1}(e^*, \tau) \cdot \Delta w - c'(e^*) = 0$. Here, $de^*/d\tau \geq 0$ due to $\frac{\partial^2 h}{\partial e_1 \partial \tau}(e^*, \tau) \geq 0$.

choices. This is always the case when the technology does not affect the marginal productivity of effort (i.e., $\frac{\partial^2 h}{\partial e_i \partial \tau} = 0$). The intuition for this finding can be best seen by inspection of (3): Since $g(\cdot)$ is single-peaked at zero, equilibrium efforts will be lower the higher $|h(e^*, a_1, \tau) - h(e^*, a_2, \tau)|$. As technology and ability are complements, a better technology makes an initially asymmetric contest with $a_1 \neq a_2$ even more asymmetric (i.e., $|h(e^*, a_1, \tau) - h(e^*, a_2, \tau)|$ increases), which further weakens both workers' incentives.

4 The Firm's Decisions

We now consider the stage where the firm decides on tournament prizes, given the technology parameter τ. Anticipating workers' equilibrium behavior $e^*(a_1, a_2, \Delta w, \tau)$, the firm chooses w and l in order to maximize expected output net of wage costs, i.e.,

$$p^2 \cdot 2h(e^*(a_H, a_H, \Delta w, \tau), a_H, \tau) + (1-p)^2 \cdot 2h(e^*(a_L, a_L, \Delta w, \tau), a_L, \tau) +$$
$$2p(1-p) \cdot [h(e^*(a_H, a_L, \Delta w, \tau), a_H, \tau) + h(e^*(a_H, a_L, \Delta w, \tau), a_L, \tau)] +$$
$$2E[\varepsilon_1] - \Delta w - 2l.$$

Thereby, the firm has to take into account the limited liability constraints $w, l \geq 0$, and the participation constraints

$$E\{l + [G(h(e^*(a_1, a_2, \Delta w, \tau), a_1, \tau) - h(e^*(a_1, a_2, \Delta w, \tau), a_2, \tau))] \cdot \Delta w$$
$$-c(e^*(a_1, a_2, \Delta w, \tau))\} \geq 0,$$

$$E\{l + [1 - G(h(e^*(a_1, a_2, \Delta w, \tau), a_1, \tau) - h(e^*(a_1, a_2, \Delta w, \tau), a_2, \tau))] \cdot \Delta w$$
$$-c(e^*(a_1, a_2, \Delta w, \tau))\} \geq 0.$$

Here, the expectation operator refers to the different possible realizations of the abilities a_1 and a_2, which are still unknown to the worker when he signs the contract.

In order to solve the firm's problem, first note that we can ignore the participation constraints: Under any ability match, each worker can ensure himself a non-negative expected utility and, hence, his reservation value, by participating in the tournament and choosing zero effort. Thus, it is rational for him to accept any contract with non-negative prizes. Furthermore, the firm optimally chooses a loser prize $l = 0$ because a higher loser prize increases the firm's labor costs but decreases workers' incentives, according to (3). Altogether, using $l = 0$ and $\Delta w = w$, the firm's optimization problem boils down to[8]

$$\max_{w\geq 0}\ p^2 \cdot 2h(e^*(a_H, a_H, w, \tau), a_H, \tau) + (1-p)^2 \cdot 2h(e^*(a_L, a_L, w, \tau), a_L, \tau) + \\ 2p(1-p) \cdot [h(e^*(a_H, a_L, w, \tau), a_H, \tau) + h(e^*(a_H, a_L, w, \tau), a_L, \tau)] - w. \quad (5)$$

Let $w^*(\tau)$ denote the solution to (5).

Now we turn to the first stage, where the firm chooses the production technology $\tau \in \{\tau_L, \tau_H\}$. The firm's profit under optimal tournament prizes is given by

$$\pi(w^*) = p^2 \cdot 2h(e^*(a_H, a_H, w^*, \tau), a_H, \tau) + (1-p)^2 \cdot 2h(e^*(a_L, a_L, w^*, \tau), a_L, \tau) + \\ 2p(1-p) \cdot [h(e^*(a_H, a_L, w^*, \tau), a_H, \tau) + h(e^*(a_H, a_L, w^*, \tau), a_L, \tau)] - w^*(\tau).$$

Although the firm faces a binary decision problem, differentiation of the objective function with respect to τ is helpful for deriving our results on the optimal technology choice. Applying the envelope theorem, the impact of

[8] For brevity we skipped $2E[\varepsilon_1]$.

technology on firm profit is given by

$$\begin{aligned}
\frac{\partial \pi(w^*)}{\partial \tau} = 2p^2 & \left\{ \frac{\partial h}{\partial e}(e^*(a_H, a_H, w^*, \tau), a_H, \tau) \frac{\partial e^*}{\partial \tau}(a_H, a_H, w^*, \tau) + \right. \\
& \left. \frac{\partial h}{\partial \tau}(e^*(a_H, a_H, w^*, \tau), a_H, \tau) \right\} + \\
2(1-p)^2 & \left\{ \frac{\partial h}{\partial e}(e^*(a_L, a_L, w^*, \tau), a_L, \tau) \frac{\partial e^*}{\partial \tau}(a_L, a_L, w^*, \tau) + \right. \\
& \left. \frac{\partial h}{\partial \tau}(e^*(a_L, a_L, w^*, \tau), a_L, \tau) \right\} + \\
2p(1-p) & \left\{ \left[\frac{\partial h}{\partial e}(e^*(a_H, a_L, w^*, \tau), a_H, \tau) + \right. \right. \\
& \left. \frac{\partial h}{\partial e}(e^*(a_H, a_L, w^*, \tau), a_L, \tau) \right] \cdot \frac{\partial e^*}{\partial \tau}(a_H, a_L, w^*, \tau) + \\
& \left. \frac{\partial h}{\partial \tau}(e^*(a_H, a_L, w^*, \tau), a_H, \tau) + \frac{\partial h}{\partial \tau}(e^*(a_H, a_L, w^*, \tau), a_L, \tau) \right\}.
\end{aligned} \tag{6}$$

The partial derivatives of h with respect to τ reflect the direct effect of a marginal technology improvement on output in a given tournament match. This effect is always positive by the assumption that $\frac{\partial h}{\partial \tau} > 0$. The remaining terms characterize the impact of an enhanced technology on workers' effort choices and, consequently, output. By the proof of Proposition 1, in the two homogeneous matches where workers are either both of low or both of high ability, equilibrium effort is increasing in the technology parameter τ, i.e., $\frac{\partial e^*}{\partial \tau}(a_k, a_k, w^*, \tau) \geq 0$ for $k = L, H$. However, if workers are heterogeneous, equilibrium effort may be decreasing, i.e., $\frac{\partial e^*}{\partial \tau}(a_H, a_L, w^*, \tau) < 0$ is possible. As outlined in the discussion of Proposition 1, $\frac{\partial e^*}{\partial \tau}(a_H, a_L, w^*, \tau) < 0$ particularly holds if effort and technology are independent and if technology and ability are complements. In such a situation, a better technology $\tau_H > \tau_L$ exacerbates the problem of asymmetric tournament competition and leads to a negative incentive effect. If this negative incentive effect dominates the direct positive impact of technology on output for all $\tau \in [\tau_L, \tau_H]$, then the firm will optimally choose the less productive technology τ_L.

Proposition 2 *If $\frac{\partial e^*}{\partial \tau}(a_H, a_L, w^*, \tau) < 0$, then the firm may prefer technology τ_L to τ_H.*

In order to identify further determinants that prevent the adoption of a superior technology, we now consider the more specific production function

$$h(e_i, a_i, \tau) = e_i + a_i\tau. \tag{7}$$

At the tournament stage, production function (7) together with condition (3) leads to equilibrium effort

$$e^* = H(g((a_1 - a_2)\tau)(w - l)), \tag{8}$$

where $H(\cdot)$ denotes the (monotonically increasing and concave) inverse function of marginal costs $c'(e_i)$.[9] Clearly, in production function (7), ability and technology are complementary, whereas the marginal productivity of effort is independent of the implemented technology. By Proposition 1, this leads to a situation where $\partial e^*(a_1, a_2, w^*, \tau)/\partial\tau < 0$ in a heterogeneous tournament match with $a_1 \neq a_2$. Since $g(\cdot)$ is single-peaked at zero, we immediately obtain this result from (8) as well.

At the stage where the firm chooses the optimal tournament prize $w^*(\tau)$, the firm's strictly concave objective function reads as

$$\begin{aligned}\pi(w) = p^2 \cdot 2[H(g(0)w) + a_H\tau] + (1-p)^2 \cdot 2[H(g(0)w) + a_L\tau] + \\ 2p(1-p) \cdot [2H(g((a_H - a_L)\tau)w) + (a_H + a_L)\tau] - w\end{aligned} \tag{9}$$

with solution $w^*(\tau)$ being implicitly given by

$$\begin{aligned}2[p^2 + (1-p)^2] \cdot H'(g(0)w^*)\, g(0) + \\ 4p(1-p)H'(g((a_H - a_L)\tau)w^*)g((a_H - a_L)\tau) = 1.\end{aligned} \tag{10}$$

At the first stage, differentiating $\pi(w^*)$ with respect to τ and making use of

[9] Concavity follows from $c'''(e_i) > 0$.

the envelope theorem yields

$$\frac{\partial \pi(w^*)}{\partial \tau} = 2\left[p^2 a_H + (1-p)^2 a_L\right] +$$
$$2p(1-p)\cdot\left[2H'\left(g((a_H-a_L)\,\tau)w^*\right)\cdot w^*\cdot(a_H-a_L)\cdot g'((a_H-a_L)\,\tau)+(a_H+a_L)\right].$$

Thus, we obtain the following result.

Corollary 1 *Let the production function be given by* (7)*. The firm will prefer* $\tau = \tau_L$ *to* $\tau = \tau_H$ *if*

$$-2H'\left(g((a_H-a_L)\,\tau)w^*\right)\cdot w^*\cdot(a_H-a_L)\cdot g'((a_H-a_L)\,\tau) > \frac{a_H}{1-p}+\frac{a_L}{p} \quad (11)$$

for all $\tau \in [\tau_L, \tau_H]$.

Both sides of condition (11) are positive since $(a_H - a_L)\cdot g'((a_H-a_L)\,\tau) < 0$. The left-hand side captures the detrimental incentive effect of a better technology, whereas the right-hand side measures the beneficial direct impact of a technology improvement on output. Condition (11) emphasizes the role of worker heterogeneity for technology choice. Clearly, the condition cannot be satisfied for a degenerate distribution of worker abilities, that is for $p \to 0$ or $p \to 1$. In that case, the probability of a heterogeneous worker match tends to zero. Consequently, the detrimental incentive effect of technology enhancement almost never occurs and, thus, the firm maximizes its profits by adopting the better technology. Using $a_H - a_L$ as a measure for worker heterogeneity provides the same insight: As $a_H - a_L$ approaches zero, the left-hand side of (11) also goes to zero so that the condition cannot be satisfied either.

Intuitively, the firm should adopt the better technology if workers' effort choices are not very responsive to incentives. Then, equilibrium efforts are rather small under either technology and, consequently, the detrimental incentive effect of a technology improvement is negligible. Effort responsiveness is low when the marginal effort cost function $c'(e_i)$ is steep and/or the winner of the tournament is determined by luck rather than effort, i.e., if the variance of the random variable ε_i is large. To formally show that this intuition is true, we now consider an example that allows to explicitly determine the tournament prize w^*.[10]

Let $\varepsilon_2 - \varepsilon_1$ be normally distributed with $\varepsilon_2 - \varepsilon_1 \sim N(0, \sigma^2)$ and effort costs be given by the exponential function $c(e_i) = \exp\{c \cdot e_i\} - 1$ with $c > 0$.[11] At the tournament stage, equilibrium effort (8) can now be written as

$$e^* = \frac{1}{c}\left[\ln\left(\frac{w-l}{c\sigma\sqrt{2\pi}}\right) - \frac{(a_1 - a_2)^2 \tau^2}{2\sigma^2}\right].$$

Obviously, e^* decreases in $|a_1 - a_2|$. If $a_1 \neq a_2$, then equilibrium effort is smaller under τ_H than under τ_L. At stage 2, the firm's objective function (9) is given by

$$\pi(w) = \frac{2}{c}\ln\left(\frac{w}{c\sigma\sqrt{2\pi}}\right) - \frac{2p(1-p)(a_H - a_L)^2 \tau^2}{c\sigma^2} + 2\tau\left(pa_H + (1-p)a_L\right) - w,$$

which yields the optimal winner prize $w^* = \frac{2}{c}$. Inserting into the firm's objective function leads to

$$\pi(w^*) = \frac{2}{c}\left[\ln\left(\frac{2}{c^2\sigma\sqrt{2\pi}}\right) - 1\right] - \frac{2p(1-p)(a_H - a_L)^2 \tau^2}{c\sigma^2} + 2\tau\left(pa_H + (1-p)a_L\right).$$

Hence, the firm will prefer $\tau = \tau_L$ to $\tau = \tau_H$ if and only if $\pi(w^*; \tau_L) > \pi(w^*; \tau_H) \Leftrightarrow$

$$\frac{p(1-p)(a_H - a_L)^2}{c\sigma^2}(\tau_H + \tau_L) > pa_H + (1-p)a_L \Leftrightarrow$$
$$\frac{Var[a]}{c\sigma^2}(\tau_H + \tau_L) > E[a] \tag{12}$$

[10] Note that, due to the implicit definition of w^*, condition (11) is still too complex to verify our previous arguments. For example, if $c'(e_i)$ is extremely steep, its inverse $H'(\cdot)$ will be very flat, which decreases $H'(g(a_H - a_L)\tau)w^*)$. Thus, condition (11) is less likely to hold. However, by (10), w^* will also be lower under a steeper marginal cost function, which increases $H'(g(a_H - a_L)\tau)w^*)$. Similarly, when the variance of ε_i is large, the density $g(\cdot)$ is flat, which tends to decrease $g((a_H - a_L)\tau)$ and $g'((a_H - a_L)\tau)$ but has an ambiguous effect on w^*.

[11] An exponential function allows for sufficiently steep cost increases to guarantee existence of a pure-strategy equilibrium in the tournament. Such cost function has also be used by Tadelis (2002), Kräkel and Sliwka (2004) and Kräkel (2008).

with $Var[a]$ denoting the variance and $E[a]$ the mean of unknown worker ability from the firm's perspective.

Condition (12) can now be nicely interpreted. Again, the left-hand side characterizes the detrimental incentive effect of a better technology, whereas the right-hand side measures the positive direct impact on expected output. The condition will be satisfied if c and σ^2 are rather small, which captures our intuition from above: If c and σ^2 were large, equilibrium efforts would be small since high marginal costs and a large influence of luck discourage both workers from implementing high effort. Then, the negative incentive effect of technology improvement is not decisive for the firm's technological choice.

Furthermore, condition (12) holds for large values of $a_H - a_L$, i.e., for a sufficiently high degree of worker heterogeneity. In that case, the negative incentive effect of a more advanced technology is particularly strong (compare (8)). This finding will be reinforced if technology itself has a significant influence on output and, hence, the outcome of the tournament, i.e., if $\tau_H + \tau_L$ is large. This also means that the firm should not adopt the better technology if output is particularly responsive to ability (i.e., $\frac{\partial h}{\partial a_i} = \tau$ is large).

Finally, we can compare the technology choices of a firm in two hypothetical situations I and II that are characterized by different ability distributions in the labor market. Let $Var[a_s] = p_s(1-p_s)(a_{Hs} - a_{Ls})^2$ denote the variance and $E[a_s] = p_s a_{Hs} + (1-p_s) a_{Ls}$ the mean of workers' unknown ability in situation s ($s = I, II$) with $E[a_I] > E[a_{II}]$. That is, situation $s = I$ offers, on average, a better worker pool than situation $s = II$. Then, condition (12) states that the firm may prefer the advanced technology only in $s = II$ but not in situation $s = I$. This is the case if $Var[a_I] - Var[a_{II}]$ is sufficiently large. In other words, although ability and technology are complements, an improved labor market (in terms of worker ability) may not foster the adoption of better technologies if the improvement is accompanied by higher talent uncertainty.

5 Uneven Contests

So far, we have focussed on asymmetric tournaments in form of "unfair contests" in the sense of O'Keeffe, Viscusi, and Zeckhauser (1984). Such contests lead to a situation where heterogeneous agents work equally hard in the tournament game. The case of "uneven contests", where workers of different abilities choose different effort levels, is analytically more complex, but yields similar results. Heterogeneous workers implement different efforts if, e.g., ability and effort are no longer assumed to be independent, i.e., $\frac{\partial^2 h}{\partial e_i \partial a_i} \neq 0$. We focus on the case $\frac{\partial^2 h}{\partial e_i \partial a_i} > 0$, which means that the marginal productivity of effort increases with the worker's ability and, consequently, effort and ability are complementary. The case $\frac{\partial^2 h}{\partial e_i \partial a_i} < 0$, where higher ability makes effort less productive, seems rather unreasonable and is therefore neglected.

It can be shown[12] that the adverse incentive effect arises for heterogeneous workers under similar circumstances as in the unfair contest. With ability and effort being complements, the more talented agent works harder than the less talented one in a heterogeneous tournament match. Then, for the more able worker, technology adoption has qualitatively the same effect on effort as in the unfair contest: If ability and technology are complements ($\frac{\partial^2 h}{\partial a_i \partial \tau} > 0$) and, in addition, effort and technology are independent ($\frac{\partial^2 h}{\partial e_i \partial \tau} = 0$),[13] the more able worker will always decrease his effort under the superior production technology. Under the same circumstances, the effect on the less talented worker's effort is ambiguous. On the one hand, as in the unfair tournament, he is discouraged by the fact that his more able colleague can take greater advantage of the new technology. However, on the other hand, due to the different effort choices, now there is a counteracting effect on effort: The reduced effort of the more able agent improves the chance for the less able worker to win the contest and thus encourages him to increase his effort. Nevertheless, since equilibrium effort of the more able worker is unambiguously reduced we should in general expect total effort $e_1^* + e_2^*$ to decrease under the advanced technology.

[12] The proofs for this subsection are given in the appendix.

[13] For example, let the production function be $h(e_i, a_i, \tau) = e_i a_i + a_i \tau$.

By contrast, if ability and technology are substitutes ($\frac{\partial^2 h}{\partial a_i \partial \tau} < 0$),[14] the more able worker will always increase his effort when the firm introduces a better technology. Again, the effect on the less able worker's equilibrium effort is ambiguous, but total effort can be expected to increase under the advanced technology. Thus, to sum up, in analogy to the case of unfair contests, the firm may prefer not to adopt the advanced technology if ability and technology are complements.

6 Conclusion

The previous analysis has shown that a firm that uses rank-order tournaments to provide its workforce with effort incentives may refrain from implementing an advanced production technology, even if the adoption of this technology is free. A necessary condition for the firm to prefer an inferior technology is that a worker's ability and the production technology are complementary, i.e., a better technology raises the productivity of more able workers more strongly. Then, under an enhanced technology, competition among heterogeneous workers becomes more uneven. As a consequence, workers are discouraged from exerting effort. If this adverse incentive effect is sufficiently strong, it outweighs the advantageous effect of an increased productivity under the new technology.

The adverse incentive effect is the stronger the more responsive the workers' effort choice is to incentives. In particular, this means that firms which are able to assess workers' performances quite precisely (i.e., σ^2 is low) are less inclined to adopt a superior production technology than firms with a less accurate monitoring technology. Thus, production and monitoring technologies are substitutes.

Moreover, higher talent uncertainty among workers exacerbates the adverse incentive effect of a new technology. Presuming that talent uncertainty decreases as workers stay longer with the firm and are promoted along the firm's hierarchy, our analysis suggests that a firm benefits more from intro-

[14] Let, e.g., the production function be $h(e_i, a_i, \tau) = e_i a_i + \frac{a_i}{\tau} + \tau$ with $\tau^2 > a_H$.

ducing new technologies on higher layers. Thus, taking into account costs for technology adoption, new technologies (e.g., computer systems) should first be implemented on higher hierarchy levels, while adoption on lower levels takes place as technology costs decrease.

We have focused on a situation where the firm can use only relative incentive schemes because workers' performance signals are unverifiable and relational contracts are not feasible. However, in practice, the firm may prefer relative performance pay to an individual incentive scheme even if the latter is, in principle, available. The reason is that rank-order tournaments have further advantages over individual performance pay. For example, under a tournament scheme, the costs of measuring performance are low because only an ordinal, unverifiable measure is needed. Furthermore, if workers are risk-averse, tournaments can lower risk costs by filtering out common shocks. Our analysis implies that, given the feasibility of different forms of incentive contracts, a firm may want to revise its incentive scheme after the adoption of a new production technology. For example, before the availability of a new production technology, the firm might prefer relative performance pay to individual incentive contracts because the former exhibits lower costs for measuring employee performance. However, after technology adoption, it might be worthwhile for the firm to invest in a monitoring technology that allows to apply individual performance pay. Then, the firm avoids the adverse incentive effect that would occur under a relative incentive scheme. In general, our analysis identifies a new comparative advantage of individual incentive pay if (i) worker ability and the production technology are complements and (ii) the adoption of advanced technologies is crucial for firm success.

Appendix – Uneven Tournaments

In this appendix, we consider the case $\frac{\partial^2 h}{\partial e_i \partial a_i} > 0$, which results in an uneven tournament. Our aim is to show that, as in the unfair tournament, an adverse incentive effect may arise under technology adoption. Analogous to the case of unfair tournaments, one can derive the first-order conditions characterizing the equilibrium effort levels e_1^* and e_2^* (compare (1) and (2)):

$$g(h(e_1^*, a_1, \tau) - h(e_2^*, a_2, \tau)) \cdot \frac{\partial h}{\partial e_1}(e_1^*, a_1, \tau) \cdot \Delta w - c'(e_1^*) = 0, \tag{13}$$

$$g(h(e_1^*, a_1, \tau) - h(e_2^*, a_2, \tau)) \cdot \frac{\partial h}{\partial e_2}(e_2^*, a_{2,} \tau) \cdot \Delta w - c'(e_2^*) = 0. \tag{14}$$

If workers are homogeneous (i.e., $a_1 = a_2$), the equilibrium is symmetric and the equilibrium effort is always non-decreasing in the technology parameter. Thus, as in an unfair tournament with equally talented workers, there is no adverse incentive effect. Now assume that workers are heterogeneous and, w.l.o.g., let worker 1 be the more able worker (i.e., $a_1 > a_2$). Then, by (13) and (14), the more talented agent works harder (i.e., $e_1^* > e_2^*$) because $\frac{\partial^2 h}{\partial e_i \partial a_i} > 0$. Define agent i's marginal benefit of increasing effort as

$$\Gamma_i := g(h(e_1^*, a_1, \tau) - h(e_2^*, a_2, \tau)) \cdot \frac{\partial h}{\partial e_i}(e_i^*, a_i, \tau) \cdot \Delta w, \quad i \neq j, \;\; i, j = 1, 2.$$

Then, by the implicit function theorem, $\frac{de_1^*}{d\tau}$ and $\frac{de_2^*}{d\tau}$ are determined by the following equation:

$$\begin{pmatrix} \frac{\partial \Gamma_1}{\partial e_1} - c''(e_1^*) & \frac{\partial \Gamma_1}{\partial e_2} \\ \frac{\partial \Gamma_2}{\partial e_1} & \frac{\partial \Gamma_2}{\partial e_2} - c''(e_2^*) \end{pmatrix} \begin{pmatrix} \frac{de_1^*}{d\tau} \\ \frac{de_2^*}{d\tau} \end{pmatrix} = - \begin{pmatrix} \frac{\partial \Gamma_1}{\partial \tau} \\ \frac{\partial \Gamma_2}{\partial \tau} \end{pmatrix}.$$

To simplify notation, define

$$A := \begin{pmatrix} \frac{\partial \Gamma_1}{\partial e_1} - c''(e_1^*) & \frac{\partial \Gamma_1}{\partial e_2} \\ \frac{\partial \Gamma_2}{\partial e_1} & \frac{\partial \Gamma_2}{\partial e_2} - c''(e_2^*) \end{pmatrix},$$

$$B := \begin{pmatrix} -\frac{\partial \Gamma_1}{\partial \tau} & \frac{\partial \Gamma_1}{\partial e_2} \\ -\frac{\partial \Gamma_2}{\partial \tau} & \frac{\partial \Gamma_2}{\partial e_2} - c''(e_2^*) \end{pmatrix},$$

$$C := \begin{pmatrix} \frac{\partial \Gamma_1}{\partial e_1} - c''(e_1^*) & -\frac{\partial \Gamma_1}{\partial \tau} \\ \frac{\partial \Gamma_2}{\partial e_1} & -\frac{\partial \Gamma_2}{\partial \tau} \end{pmatrix}.$$

By Cramer's rule, $\frac{de_1^*}{d\tau} = \det B / \det A$ and $\frac{de_2^*}{d\tau} = \det C / \det A$. To determine the sign of $\det A$, first note that $\frac{\partial \Gamma_1}{\partial e_2} = -\frac{\partial \Gamma_2}{\partial e_1}$. Furthermore, concavity of a worker's optimization problem requires that $\frac{\partial \Gamma_i}{\partial e_i} - c''(e_i^*) < 0$. Hence, we obtain $\det A > 0$. For the matrices B and C, we have

$$\det B = -\frac{\partial \Gamma_1}{\partial \tau}\left(\frac{\partial \Gamma_2}{\partial e_2} - c''(e_2^*)\right) + \frac{\partial \Gamma_1}{\partial e_2}\frac{\partial \Gamma_2}{\partial \tau},$$
$$\det C = -\frac{\partial \Gamma_2}{\partial \tau}\left(\frac{\partial \Gamma_1}{\partial e_1} - c''(e_1^*)\right) + \frac{\partial \Gamma_2}{\partial e_1}\frac{\partial \Gamma_1}{\partial \tau}.$$

Because $e_1^* > e_2^*$ and $g(\cdot)$ is single-peaked at zero, we obtain $\frac{\partial \Gamma_1}{\partial e_2} > 0$ and $\frac{\partial \Gamma_2}{\partial e_1} < 0$. Intuitively, the harder working agent 1 benefits more from increasing effort if agent 2 catches up. On the other hand, if agent 1 increases his effort, it is less beneficial for the less able agent 2 to exert more effort. Furthermore, the marginal impact of a better technology on Γ_i is given by

$$\frac{\partial \Gamma_i}{\partial \tau} = \left[g'(\cdot)\frac{\partial(h(e_1^*, a_1, \tau) - h(e_2^*, a_2, \tau))}{\partial \tau}\frac{\partial h}{\partial e_i}(e_i^*, a_i, \tau) + g(\cdot)\frac{\partial^2 h}{\partial e_i \partial \tau}(e_i^*, a_i, \tau)\right]\Delta w.$$

If ability and technology are complements (i.e., $\frac{\partial^2 h}{\partial a_i \partial \tau} > 0$), and effort and technology are independent (i.e., $\frac{\partial^2 h}{\partial e_i \partial \tau} = 0$), we obtain $\frac{\partial \Gamma_i}{\partial \tau} < 0$. Consequently, in this case, $\det B < 0$ and worker 1's effort is decreasing in τ. Thus, for worker 1, we have a similar situation as in the unfair tournament: He always lowers his effort under an advanced technology if $\frac{\partial^2 h}{\partial a_i \partial \tau} > 0$ and $\frac{\partial^2 h}{\partial e_i \partial \tau} = 0$. Intuitively, a better technology lowers his own and his colleague's marginal benefit of increasing effort, Γ_1 and Γ_2 respectively, so that worker 1 unambiguously prefers to lower effort. By contrast, the sign of $\det C$ and, hence, the effect of an advanced technology on worker 2's effort is ambiguous. The reason is that there are two counteracting effects: First, the new technology lowers Γ_2. However, the lower effort of worker 1 increases Γ_2, thereby encouraging worker 2 to raise his effort. Thus, it is not clear whether worker 2 will increase or decrease effort. Altogether, since the equilibrium effort of the more able worker is unambiguously reduced, the overall effect of a better technology on total effort should be negative. Technically, this will be the case if

$$\frac{\partial\left(e_1^* + e_2^*\right)}{\partial \tau} = \underset{(+)}{\frac{1}{\det A}} \left(\underbrace{-\frac{\partial \Gamma_1}{\partial \tau}\left(\frac{\partial \Gamma_2}{\partial e_2} - c''(e_2^*)\right)}_{(-)} + \underset{(-)}{\frac{\partial \Gamma_1}{\partial e_2}\frac{\partial \Gamma_2}{\partial \tau}} \right.$$

$$\left. \underbrace{-\frac{\partial \Gamma_2}{\partial \tau}\left(\frac{\partial \Gamma_1}{\partial e_1} - c''(e_1^*)\right)}_{(-)} + \underset{(+)}{\frac{\partial \Gamma_2}{\partial e_1}\frac{\partial \Gamma_1}{\partial \tau}} \right) < 0.$$

If ability and technology are substitutes (i.e., $\frac{\partial^2 h}{\partial a_i \partial \tau} < 0$) and $\frac{\partial^2 h}{\partial e_i \partial \tau} = 0$, we have $\frac{\partial \Gamma_i}{\partial \tau} > 0$. Hence, $\det B > 0$ and worker 1 increases his effort under technology adoption. The effect on worker 2's effort is again ambiguous: The technology effect favors higher effort. However, the higher effort of his colleague discourages worker 2.

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